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Search for Higgs boson decays to beyond-the-Standard-Model light bosons in four-lepton events with the ATLAS detector at $\sqrt{s} = 13$ TeV

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Abstract: A search is conducted for a beyond-the-Standard-Model boson using events where a Higgs boson with mass 125 GeV decays to four leptons ($\ell = e$ or μ). This decay is presumed to occur via an intermediate state which contains one or two on-shell, promptly decaying bosons: $H \to ZX/XX \to 4\ell$, where X is a new vector boson Z_d or pseudoscalar a with mass between 1 and 60 GeV. The search uses pp collision data collected with the ATLAS detector at the LHC with an integrated luminosity of 36.1 fb^{-1} at a centre-of-mass energy $\sqrt{s} = 13$ TeV. No significant excess of events above Standard Model background predictions is observed; therefore, upper limits at 95% confidence level are set on model-independent fiducial cross-sections, and on the Higgs boson decay branching ratios to vector and pseudoscalar bosons in two benchmark models.

Keywords: Beyond Standard Model, Hadron-Hadron scattering (experiments)

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1 Introduction

Following the discovery of the Higgs boson by the ATLAS and CMS collaborations [1, 2] at the Large Hadron Collider (LHC), a comprehensive programme of measurements of the properties of this particle is underway. These measurements could uncover deviations from the expected branching ratios for the decays of a Standard Model (SM) Higgs boson or allow for the possibility of decays into non-SM particles. Existing measurements constrain the non-SM or "exotic" branching ratio of the Higgs boson to less than approximately 30% at 95% confidence level (CL) [3–5].

Exotic Higgs boson decays have been proposed as a way to search for evidence of new physics. Due to the extremely narrow decay width of the Higgs boson predicted by the SM, the addition of even a small coupling to a new light state could open up sizeable new decay modes. In addition, new particles may couple preferentially to the Higgs boson since it provides a possible "portal" for hidden-sector particles to interact with SM particles [6–9]. Such decays are predicted by many theories of physics beyond the SM. For example, they are predicted in theories with a hidden ("dark") sector [10–19] and in those with an extended Higgs sector such as the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [20–24]. They are also predicted in several models of dark matter [25–30], models that explain astrophysical observations of positron excesses [31–33], models with a first-order electroweak phase transition [34, 35], and theories with neutral naturalness [36–38]. The processes under study here are referred to as $pp \to H \to ZX/XX \to 4\ell$, with Z being the SM Z boson and with X representing a possible new vector boson Z_d or a new pseudoscalar boson a. Section 2 provides an introduction to the theoretical background and specific models examined in this paper.

The search uses pp collision data at a centre-of-mass energy $\sqrt{s} = 13\,\text{TeV}$ collected by the ATLAS detector (described in section 3) at the LHC in 2015 and 2016 corresponding to an integrated luminosity of $36.1\,\text{fb}^{-1}$. Same-flavour decays of the new particle to pairs of electrons and muons are considered, giving rise to the $4e$, $2e2\mu$, and 4μ final states for particles in the mass range from 15 GeV to $m_H/2$, where $m_H = 125\,\text{GeV}$. For lower masses, targeting the range from 1 GeV to 15 GeV, only the 4μ final state is explored. Final states including τ leptons are not considered in either mass range. The event reconstruction is discussed in section 4.

The search for $H \to ZX \to 4\ell$ in an X mass range between 15 GeV and 55 GeV is covered in section 5, while the $H \to XX \to 4\ell$ searches are included in sections 6 and 7 for $15\,\text{GeV} < m_X < 60\,\text{GeV}$ and $1\,\text{GeV} < m_X < 15\,\text{GeV}$, respectively.[1] Model interpreta-

[1] The reason for the two ranges being different is that in the $H \to ZX \to 4\ell$ search the mass distributions of the X and the Z bosons begin to overlap significantly for values larger than 55 GeV, thus inhibiting unambiguous identification of the Z and the new bosons. This is not the case in the $H \to XX \to 4\ell$ search where a Z veto is applied.

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tions and discussions are presented in section 8. Finally, the conclusions of the search are presented in section 9.

This paper builds on the previous work of ref. [39], in which a similar analysis is reported with data collected at $\sqrt{s} = 8\,\text{TeV}$.

2 Benchmark models

Two well-motivated benchmark models that predict exotic decays to light beyond-the-Standard-Model (BSM) bosons are summarised below, and are used later in this paper when interpreting the results. In the first BSM benchmark model, the SM is extended with a dark-sector U(1) group, denoted $\text{U}(1)_d$, leading to the appearance of a BSM vector boson, Z_d. In the second BSM benchmark model, there are two Higgs doublets and an additional singlet scalar field (2HDM+S). This leads to the appearance of a BSM pseudoscalar boson, a. The Z_d boson and the a pseudoscalar could each comprise the intermediate state in the decays $H \to ZX \to 4\ell$ and $H \to XX \to 4\ell$, where the first benchmark model is considered for a higher mass range and the second for a lower mass range.

2.1 Vector-boson model

Hidden- or dark-sector states appear in many extensions to the SM [10–19, 40]. The dark-sector states allow a theoretically plausible route for generation of the particle content necessary to account for the astrophysical evidence of dark matter. For example, fermionic dark-matter candidates [30] or dark-sector couplings to normal matter might explain astrophysical observations of positron excesses [31–33].

A dark sector is introduced with an additional $\text{U}(1)_d$ dark gauge symmetry [14–19], coupled to the SM through kinetic mixing with the hypercharge gauge field [41–43]. The gauge boson of the symmetry is the Z_d vector boson. In this hypercharge portal scenario, the kinetic mixing parameter ϵ controls the coupling strength of the dark vector boson to SM particles, which in turn determines the lifetime of the Z_d boson. The branching ratios of the Z_d are independent of the kinetic mixing strength and are instead determined by the gauge coupling. This coupling leads to a significant fraction of decays ($\approx 15\%$) to pairs of electrons or muons. For Z_d masses between 1 GeV and 60 GeV, the decay would be prompt (relative to the vertex resolution of the ATLAS detector) for $\epsilon \gtrsim 10^{-5}$ [14]. For smaller values of ϵ, the displaced decays provide a unique signature, which has been previously searched for with the ATLAS detector in 8 TeV collisions [44]. For Z_d masses below a few GeV and small values of ϵ, the decay products would be highly collimated and require a special analysis [45]. Another possibility involves a mass mixing between the Z boson and Z_d, facilitating the decay of the Z_d to SM particles. In this mechanism, the strength of the mixing is determined by mass mixing parameter δ [16, 17].

If the $\text{U}(1)_d$ symmetry is broken by the introduction of a dark Higgs boson, there could also be mixing between the SM Higgs boson and the dark Higgs boson [14–19]. In this scenario, the Higgs portal coupling κ controls the strength of the Higgs coupling to dark vector bosons. The observed Higgs boson would be the lighter one of an extended Higgs sector and could also decay into dark-sector particles.

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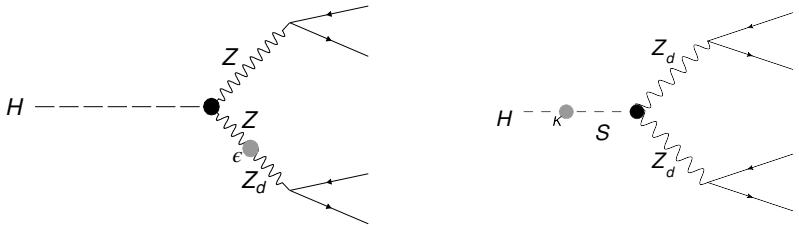

Figure 1. Exotic Higgs boson decays to four leptons induced by intermediate dark vector bosons via (left) the hypercharge portal and (right) the Higgs portal, where S is a dark Higgs boson [14]. The Z_d gauge boson decays to SM particles through kinetic mixing with the hypercharge field or through mass mixing with the Z boson. The HZZ_d vertex factor is proportional to ϵ whereas the HZ_dZ_d vertex factor is proportional to κ.

For the processes studied in this paper, the decay $H \to ZZ_d$ probes the parameter space of ϵ and m_{Z_d}, and does not depend on the presence of mixing between the SM Higgs boson and the dark-sector Higgs boson, κ. However, this BSM signal is indistinguishable from SM $H \to ZZ^*$ on an event-by-event basis, and therefore must emerge as a resonance in the dilepton mass above this background process. The SM background to the $H \to Z_dZ_d$ process, however, is more easily separated from the signal. This feature makes the latter channel potentially sensitive to much smaller values of kinetic mixing, where the only requirement is that the kinetic mixing must be large enough for the Z_d to decay promptly. However, this process depends on the presence of mixing between the SM Higgs boson and dark-sector Higgs boson, and therefore probes the parameter space of κ and m_{Z_d}.

Feynman diagrams of both processes are shown in figure 1. These processes are included in the Hidden Abelian Higgs Model (HAHM) that is used in this paper as the benchmark vector-boson model [14].

The presence of the dark sector could be inferred either from deviations from the SM-predicted rates of Drell-Yan (DY) events or from Higgs boson decays through exotic intermediate states. Model-independent upper bounds from electroweak constraints on the kinetic mixing parameter, ϵ, below 0.03 are reported in refs. [14, 46, 47] for dark vector bosons with masses between 1 GeV and 200 GeV. Upper bounds on the kinetic mixing parameter based on searches for dilepton resonances, $pp \to Z_d \to \ell\ell$, below the Z boson mass, are found to be in range of 0.005–0.020 for dark vector bosons with masses between 20 GeV and 80 GeV [48]. In the mass range of 10 MeV–10 GeV, values of ϵ above $\sim 10^{-3}$ are ruled out [49–54].The experiments at the LHC are the only ones sensitive to the production of Higgs bosons, and this makes possible the search for the presence of a Higgs portal presented here. Constraints on the Higgs mixing parameter κ are probed through the $H \to Z_dZ_d \to 4\ell$ search while constraints on the kinetic mixing parameter and the mass-mixing parameter δ can be obtained through the $H \to ZZ_d \to 4\ell$ search.

2.2 Pseudoscalar-boson model

Another possibility to extend the SM with a hidden sector is to consider two-Higgs-doublet models extended by one complex scalar singlet field (2HDM+S) [15].

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Two-Higgs-doublet models predict two charged scalars ($H^{\pm}$), two neutral scalars (H, $\mathbb{H}$) and one neutral pseudoscalar (A). The real mass eigenstate H is considered to be the observed Higgs boson, while other states are taken to be heavy in the decoupling limit to ensure that highly non-standard Higgs decays (e.g. involving CP-violation) which are significantly constrained by existing data, are avoided [55, 56]. The scalar singlet added to 2HDM only couples to the two Higgs complex fields in the potential and has no Yukawa couplings. Therefore, all of its couplings to SM fermions are acquired through mixing of the scalar field with the Higgs complex fields, which needs to be small to preserve the SM nature of the Higgs sector.

With these assumptions, the decay $H \to aa$ is allowed, where a is a light pseudoscalar mass eigenstate mostly composed of the imaginary part of the singlet field.[2] The aforementioned constraints on two-Higgs-doublet models can be incorporated in the 2HDM+S by choosing a region of the 2HDM phase space not yet excluded, and giving the real and imaginary components of the singlet separate masses and small mixings to the Higgs doublets. The branching ratios of a into fermions are determined by the Yukawa couplings of a to fermions, and lead to a rich decay phenomenology [15], albeit with typically negligible branching ratio to pairs of electrons, and smaller branching ratios to pairs of muons than the dark vector bosons described in the previous section. Among all the models predicting different decay possibilities, type II are theoretically well motivated,[3] since light pseudoscalars can correspond to the R-symmetry limit of the NMSSM [57, 58], which elegantly solves the μ-problem of the MSSM [59] and greatly reduces the fine-tuning and little-hierarchy problems. Furthermore, in the NMSSM the branching ratio for $H \to aa$ can be significant. Type-II models can also predict a significant branching ratio for $a \to \mu\mu$, especially in the range $2m_\mu < m_a < 2m_\tau$, with values ranging from 10^{-2} to 10^{-1} for some regions of the parameter space [15].

Several searches for a Higgs boson decaying to electrons, muons, τ leptons or b-jets via two pseudoscalars have been performed at both the LHC and the Tevatron. The DØ and ATLAS collaborations have searched for a signal of $H \to aa \to 2\mu 2\tau$ in the a boson mass ranges $3.7 \leq m_a \leq 19\,\text{GeV}$ and $3.7 \leq m_a \leq 50\,\text{GeV}$, respectively [60, 61]. The DØ and CMS collaborations have searched for the signature $H \to aa \to 4\mu$ in the range $2m_\mu \leq m_a \leq 2m_\tau$ [60, 62]. The CMS collaboration has additionally searched for $H \to aa \to 4\tau, 2\mu 2\tau, 2\mu 2b$ in the range $5\,\text{GeV} \leq m_a \leq 62.5\,\text{GeV}$ [63] and the ATLAS collaboration for $H \to aa \to 4b$ in the range $20\,\text{GeV} \leq m_a \leq 60\,\text{GeV}$ [64]. These searches have led to limits on the branching ratio of the Higgs boson decaying to aa, scaled by the ratio of the production cross-section of the Higgs boson that is searched for to that predicted by the SM, $\sigma(H)/\sigma_{\text{SM}} \times \mathcal{B}(H \to aa)$, between 1% and 3% for pseudoscalar-boson masses between 1 GeV and 3 GeV and between 10% and 100% for masses larger than 5 GeV, assuming a 2HDM+S Type-II model with $\tan\beta = 5.0$.

[2]The pseudoscalar state is $a = \cos\theta_a S_I + \sin\theta_a A$, where $\theta_a \ll 1$ is a small mixing angle and S_I is the imaginary part of the complex singlet field.

[3]The right-handed states d_R and e_R couple to H_1, u_R to H_2, where H_1 and H_2 are the two Higgs doublets. See ref. [15] for more information.

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3 ATLAS detector

The ATLAS experiment [65] is a multi-purpose particle physics detector with forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[4] The interaction point is surrounded by an inner detector (ID) tracking system, a calorimeter system, and a muon spectrometer (MS). The ID covers $|\eta| < 2.5$ and consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The ID is surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field. One significant upgrade for Run 2 is the presence of the insertable B-layer (IBL) [66], an additional pixel layer close to the interaction point, which provides high-resolution measurements at small radius to improve the tracking performance. The calorimeter system features a high-granularity lead/liquid-argon (LAr) sampling calorimeter that measures the energy and the position of electromagnetic showers within $|\eta| < 4.9$. LAr sampling calorimeters are also used to measure hadronic showers in the endcap ($1.5 < |\eta| < 3.2$) and forward ($3.1 < |\eta| < 4.9$) regions, while an steel/scintillator tile calorimeter measures hadronic showers in the central region ($|\eta| < 1.7$). The MS surrounds the calorimeters and consists of three large superconducting air-core toroid magnets, each with eight coils, a system of precision tracking chambers ($|\eta| < 2.7$), and fast trigger chambers ($|\eta| < 2.4$). For Run 2 the ATLAS detector has a two-level trigger system. The first-level trigger (Level-1 trigger) is implemented in hardware and uses a subset of the detector information to reduce the accepted rate to 100 kHz. This is followed by a software-based trigger (called high-level trigger) that reduces the rate of events recorded to 1 kHz.

4 Event reconstruction

The three analyses presented in this paper all follow a similar event reconstruction and selection procedure. This section describes the basic event selection and lepton reconstruction requirements that are common to all three analyses. Table 1 summarises the event selection used in the three analyses that are described in further detail in sections 5–7.

Events are preselected in accord with trigger requirements and basic event requirements such as the existence of a reconstructed primary vertex [67], which has the largest sum of p_{T}^2 of the associated tracks. For each event, a selection is applied to the reconstructed final-state leptons. The event is required to have at least four leptons. These leptons are combined into dileptons, and the dileptons are paired into quadruplets. Quadruplets are then filtered by selection criteria specific to each analysis, and a single quadruplet (with a specific dilepton pairing) is selected according to a ranking metric that favours pairings

[4] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. The transverse momentum p_{T} and other transverse variables, are defined as the variables' component in the $x-y$ plane, the transverse energy E_{T} is defined as $\sqrt{m^2 + p_{\mathrm{T}}^2}$, where m represents the mass of a considered object. The distance in the pseudorapidity-azimuthal-angle space is defined as dR or $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

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compatible with either a ZX or XX intermediate state, depending on the analysis. If there are no quadruplets in the event that meet the selection criteria then the event is discarded. Final event selections are based on properties of this selected quadruplet and the corresponding dilepton pair.

4.1 Trigger and event preselection

Events are preselected by single-lepton, dilepton, or trilepton triggers [68], with a combined efficiency very close to 100% (relative to the signal region events surviving all other event selections). Trigger thresholds were increased slightly throughout the run to compensate for increasing peak instantaneous luminosity delivered by the LHC. The lowest p_{T} thresholds for the single-lepton triggers ranged from 24 GeV to 26 GeV. Dielectron (dimuon) trigger thresholds ranged from 2×12 GeV (2×10 GeV) to 2×17 GeV (22, 8 GeV). Trielectron (trimuon) triggers had thresholds of 17, 9, 9 GeV (3×6 GeV). In the low-mass selection, only the muon-based triggers are used. The events must have at least one primary vertex [67] with two or more associated tracks with $p_{\mathrm{T}} > 400$ MeV and satisfy cleaning criteria [69] designed to reject events with excessive noise in the calorimeters.

4.2 Lepton reconstruction

An electron is reconstructed from a cluster of energy deposits in the electromagnetic calorimeter matched to a high-quality track in the ID. Its momentum is computed from the cluster energy and the direction of the track. Electrons are required to have $|\eta| < 2.47$ and $p_{\mathrm{T}} > 7$ GeV. Electrons can be distinguished from other particles using several identification criteria that rely on the shapes of electromagnetic showers as well as tracking and track-to-cluster matching quantities. Following the description in ref. [70], the output of a likelihood function taking these quantities as input is used to identify electrons, choosing the loose working point, but with the additional requirement of a hit presence in the innermost layer of the ID.[5]

A muon is reconstructed by matching a track or track segment reconstructed in the MS to a track reconstructed in the ID [71]. Its momentum is calculated by combining the information from the two systems and correcting for energy deposited in the calorimeters. In regions of limited coverage by the MS ($|\eta| < 0.1$), muons can be reconstructed by matching ID tracks to calorimeter signals consistent with a minimum-ionising particle (calorimeter-tagged muons). In regions outside the ID acceptance ($2.5 < |\eta| < 2.7$), muon reconstruction can also be extended by using tracks in the MS (stand-alone muons). Reconstructed muons are required to pass the requirements of the loose working point to maximise the reconstruction efficiency while providing good-quality muon tracks [71]. Muons are required to have $|\eta| < 2.7$ and $p_{\mathrm{T}} > 5$ GeV. Calorimeter-tagged muons must have $p_{\mathrm{T}} > 15$ GeV.

Leptons are required to originate from the hard-scattering vertex, defined as the primary vertex in the pre-selection. The longitudinal impact parameter of each lepton track, calculated relative to the hard-scattering vertex and multiplied by $\sin\theta$ of the track, is

[5] When no measurement is expected in the innermost layer of the pixel detector, the requirement is transferred to the next-to-innermost pixel layer.

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required to be smaller than 0.5 mm. Furthermore, muons must have a transverse impact parameter calculated relative to the beam line smaller than 1 mm in order to reject muons originating from cosmic rays. The significance of the transverse impact parameter calculated relative to the beam line is required to be less than three (five) for muons (electrons). Stand-alone muons are exempt from all three requirements, as they do not have an ID track.

The leptons are required to be isolated from other particles using ID track information and calorimeter information. The sum of the transverse energy ΣE_{T} of other topological clusters [72] in the cone of $\Delta R = 0.2$ around the electron (muon) is required to be less than 20% (30%) of the p_{T} of the electron (muon). The Σp_{T} of tracks within a variable-width cone of $\Delta R = \min(0.2, 10\,\mathrm{GeV}/p_{\mathrm{T}})$ ($\Delta R < \min(0.3, 10\,\mathrm{GeV}/p_{\mathrm{T}})$) of the electron (muon) must be less than 15% of the p_{T} of the electron (muon). Contributions to the isolation cones from other leptons in the quadruplet are subtracted before applying the requirements.

Overlap removal is applied to avoid identifying the same detector signature as multiple electrons, muons or jets. Electrons sharing an ID track with a selected muon are ignored, except if the muon is only calorimeter-tagged, in which case the muon is ignored instead. Electrons sharing their track or cluster in the calorimeter with a selected higher-p_{T} electron are ignored.

4.3 Definition of invariant-mass kinematic variables

For all three analyses, the convention is adopted that m_{12} and m_{34} are the invariant masses of the two dileptons that make up a quadruplet, with the defining constraint that $|m_{12} - m_Z| < |m_{34} - m_Z|$, where m_Z is the mass of the Z boson[6] [73]. Thus m_{12} identifies the primary pair and m_{34} is the secondary pair.

In the case of quadruplets formed from four electrons or four muons, alternate pairings of same-flavour opposite-sign leptons can be formed. The invariant masses of these alternate pairings are denoted by m_{14} and m_{32}, where the positively charged lepton from the primary pair is paired with the negatively charged lepton from the secondary pair to compute m_{14}, and the positively charged lepton from the secondary pair is paired with the negatively charged lepton from the primary pair to compute m_{32}.

4.4 Summary of analysis event selections

Table 1 summarises the event selection used in the three analyses that are described in further detail in sections 5–7, and signal efficiencies of these selections with respect to a minimal fiducial volume are shown in figures 7a and 8a of section 8.1.

5 $H \to ZX \to 4\ell$ analysis

5.1 Monte Carlo simulation

Samples of events with $H \to ZZ_d \to 4\ell$, where the Higgs boson with mass $m_H = 125\,\mathrm{GeV}$ was produced in the gluon-gluon fusion mode (ggF), were generated using the Hidden

[6] Put another way, m_{12} is the invariant mass of the dilepton that is closer to the Z boson mass, and m_{34} is the invariant mass of the other dilepton in the quadruplet.

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<table>
<tr><th></th><th>$H \to ZX \to 4\ell$
$(15\,\text{GeV} < m_X < 55\,\text{GeV})$</th><th>$H \to XX \to 4\ell$
$(15\,\text{GeV} < m_X < 60\,\text{GeV})$</th><th>$H \to XX \to 4\mu$
$(1\,\text{GeV} < m_X < 15\,\text{GeV})$</th></tr>
<tr><td rowspan="3">Quadruplet selection</td><td colspan="3">- Require at least one quadruplet of leptons consisting of two pairs of same-flavour opposite-sign leptons
- Three leading-p_T leptons satisfying $p_\text{T} > 20\,\text{GeV}$, 15 GeV, 10 GeV
- At least three muons are required to be reconstructed by combining ID and MS tracks in the 4μ channel</td></tr>
<tr><td>- Select best quadruplet (per channel) to be the one with the (sub)leading dilepton mass (second) closest to the Z mass
- $50\,\text{GeV} < m_{12} < 106\,\text{GeV}$
- $12\,\text{GeV} < m_{34} < 115\,\text{GeV}$
- $m_{12,34,14,32} > 5\,\text{GeV}$</td><td colspan="2">Leptons in the quadruplet are responsible for firing at least one trigger. In the case of multi-lepton triggers, all leptons of the trigger must match to leptons in the quadruplet</td></tr>
<tr><td colspan="2">$\Delta R(\ell,\ell') > 0.10$ (0.20) for same-flavour (different-flavour) leptons in the quadruplet</td><td>—</td></tr>
<tr><td>Quadruplet ranking</td><td>Select first surviving quadruplet from channels, in the order: 4μ, $2e2\mu$, $2\mu2e$, $4e$</td><td colspan="2">Select quadruplet with smallest $\Delta m_{\ell\ell} = |m_{12} - m_{34}|$</td></tr>
<tr><td rowspan="3">Event selection</td><td colspan="2">$115\,\text{GeV} < m_{4\ell} < 130\,\text{GeV}$</td><td>$120\,\text{GeV} < m_{4\ell} < 130\,\text{GeV}$</td></tr>
<tr><td rowspan="2"></td><td colspan="2">$m_{34}/m_{12} > 0.85$
Reject event if:
$(m_{J/\Psi} - 0.25\,\text{GeV}) < m_{12,34,14,32} < (m_{\Psi(2S)} + 0.30\,\text{GeV})$, or
$(m_{\Upsilon(1S)} - 0.70\,\text{GeV}) < m_{12,34,14,32} < (m_{\Upsilon(3S)} + 0.75\,\text{GeV})$</td></tr>
<tr><td>$10\,\text{GeV} < m_{12,34} < 64\,\text{GeV}$
$4e$ and 4μ channels:
$5\,\text{GeV} < m_{14,32} < 75\,\text{GeV}$</td><td>$0.88\,\text{GeV} < m_{12,34} < 20\,\text{GeV}$
No restriction on alternative pairing</td></tr>
</table>

Table 1. Summary of the event selection of the different analyses described in this paper. The quarkonia resonance masses $m_{J/\Psi}, m_{\Psi(2S)}, m_{\Upsilon(1S)}$, and $m_{\Upsilon(3S)}$ are taken from ref. [73].

Abelian Higgs Model (HAHM) [18, 19]. The event generator MadGraph5_aMC@NLO v2.2.3 [74] with the NNPDF23 [75] parton distribution functions (PDFs) at leading order (LO) was used. Pythia8 [76] (v8.170) with the A14 parameter set [77] was used for the modelling of the parton shower, hadronisation and underlying event. Nine samples were generated in the range $15 \leq m_{Z_d} \leq 55\,\text{GeV}$ with a 5 GeV step corresponding to different Z_d mass hypotheses. The model parameters ϵ and κ were adjusted so that only $H \to ZZ_d \to 4\ell$ decays were generated ($\epsilon \gg \kappa$). The samples were normalised using the SM Higgs boson production cross-section $\sigma_\text{SM}(gg\text{F}) = 48.58$ pb and the $\mathcal{B}(H \to ZZ^* \to 4\ell) = 1.25 \times 10^{-4}$ taken from ref. [78], as this branching ratio corresponds approximately to the upper limit set in the previous search [39]. Final states with τ leptons are not considered in this analysis and thus were not generated. The background processes considered for this search follow those used in the $H \to ZZ^* \to 4\ell$ measurement [79], and consist of:

> ***$H \to ZZ^* \to 4\ell$:*** the Higgs boson production through ggF [80], vector-boson fusion (VBF) [81], and in association with a vector boson (VH) [82], was simulated using the Powheg-Box v2 MC event generator [83–85] with the PDF4LHC NLO PDF set [86]. For Higgs boson production in association with a heavy quark pair, events were simulated with MadGraph5_aMC@NLO (v.2.2.3 for $t\bar{t}H$ and v.2.3.3 for $b\bar{b}H$) [74],

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using the CT10 NLO PDF set [87] for $t\bar{t}H$ and the NNPDF23 PDF set [75] for $b\bar{b}H$. For the ggF, VBF, VH, and $b\bar{b}H$ production mechanisms, Pythia8 [88] was used for the $H \to ZZ^* \to 4\ell$ decay as well as for parton showering, hadronisation and underlying event using the AZNLO parameter set [89]. For showering in the $t\bar{t}H$ process, Herwig++ [90] was used with the UEEE5 parameter set [91]. The Higgs boson production cross-sections and decay branching ratios, as well as their uncertainties, are taken from refs. [78, 92, 93]. This background is approximately 64% of the total background prediction.

$ZZ^* \to 4\ell$: the non-resonant SM $ZZ^* \to 4\ell$ process was simulated using Sherpa 2.2.2 [94–96] for quark-antiquark annihilation, using the NNPDF3.0 NNLO PDF set. The loop-induced gg-initiated ZZ^* production was modelled with gg2vv [97] interfaced to Pythia8, where s-channel H diagrams were omitted to avoid double-counting this contribution, using the CT10 PDFs. The latter process was calculated at LO and receives large QCD corrections at NLO. The cross-section of the sample was therefore multiplied by an NLO/LO K-factor of 1.70 ± 0.15 [98]. This background contributes with approximately 30% of the total prediction.

VVV, $t\bar{t}+V$: the triboson backgrounds ZZZ, WZZ, and WWZ with four or more leptons originating from the hard scatter were produced with Sherpa 2.1.1 [94–96, 99–102]. The all-leptonic $t\bar{t}Z$ and $t\bar{t}W$ processes were simulated with MadGraph5_aMC@NLO interfaced to Pythia8 with the A14 parameter set. This background is approximately 0.5% of the total prediction.

Reducible background: processes like Z + jets, $t\bar{t}$ and WZ, produce less than four prompt leptons but can contribute to the selection through jets misidentified as leptons. Z + jets events were modelled using Sherpa 2.2.2. The $t\bar{t}$ background was generated with Powheg-Box interfaced to Pythia6 [103] for parton shower and hadronisation and underlying event. The WZ production was modelled using Powheg-Box plus Pythia8 and the AZNLO parameter set. This background is approximately 6% of the total prediction.

The generation of the simulated samples includes the effect of multiple pp interactions in the same and nearby bunch crossings (pile-up). This was simulated at LO with Pythia8 using MSTW 2008 PDFs [104] and the A2 tune [105]. The samples were then passed through a simulation of the ATLAS detector [106] based on GEANT4 [107]. Weights were applied to the simulated events to correct for the small differences relative to data in the reconstruction, identification, isolation, and impact parameter efficiencies for electrons and muons [70, 71]. Furthermore, the lepton momentum scales and resolutions were adjusted to match the data [71, 108].

5.2 Event selection

All possible combinations of quadruplets are formed by selecting two same-flavour opposite-sign (SFOS) lepton pairs. Each quadruplet must not include more than one stand-alone

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or calorimeter-tagged muon, and its three leading leptons must have p_{T} (E_{T}) > 20, 15, 10 GeV.[7] Then a quadruplet per final state is chosen so that the leading pair is defined as the SFOS pair with the mass m_{12} closest to the Z boson mass and the subleading pair is defined as the SFOS pair with the mass m_{34} second closest to the Z boson mass. From this point, the analysis selection proceeds in parallel for the four final states (4μ, $2e2\mu$, $2\mu2e$, $4e$).

For each final state, m_{12} is required to be in the range of $50 - 106$ GeV, while m_{34} is required to be in the range of 12–115 GeV. A separation of $\Delta R > 0.10$ (0.20) is required for all possible pairings of same-flavour (different-flavour) leptons in the quadruplet. Quadruplets are removed if an alternative same-flavour opposite-sign dilepton mass is less than 5 GeV. Then the loose calorimeter- and track-based isolation as well as impact parameter requirements explained in section 4.2 are imposed on the leptons. As the four leptons should originate from a common vertex point, a requirement on the χ^2 value of a common-vertex fit is applied, corresponding to a signal efficiency of 99.5% for all decay channels. If more than one quadruplet passes the selection, the channel with the highest expected signal rate is selected, in the order: 4μ, $2e2\mu$, $2\mu2e$ and $4e$. At this point only one quadruplet remains. In order to improve the four-lepton mass reconstruction, final-state radiation photons arising from any of the lepton candidates in the quadruplet are added to the 4ℓ system using the same strategy as in ref. [109]. Events are then classified into $2\ell2\mu$ and $2\ell2e$ final states. The signal region is defined by the window of the four-lepton invariant mass $m_{4\ell} \in [115, 130]$ GeV.

5.3 Background estimation

The dominant background contribution comes from $H \to ZZ^* \to 4\ell$, followed by non-resonant SM ZZ^* production. Triboson processes as well as $t\bar{t}+V$ processes are sources of smaller backgrounds. The background processes described above are estimated from simulation and normalised with the theoretical calculations of their cross-section as described in section 5.1.

The reducible background is estimated using data-driven techniques. Different approaches are followed for the $2\ell2\mu$ and $2\ell2e$ final states [109]. The procedure to estimate the normalisation of these backgrounds is explained in ref. [79]. The shapes of the Z+jets and $t\bar{t}$ backgrounds for the m_{34} distribution are taken from simulation and normalised using the inclusive data-driven estimate. For the WZ production, as the background sources are different between the two channels, this background is included in the data-driven estimate for the $2\ell2e$ final state, while it is added from simulation for the $2\ell2\mu$ final state.

5.4 Systematic uncertainties

Imperfect knowledge of the parameters affecting the measurements either from simulated or from data-driven estimates leads to systematic uncertainties which affect the normalisation or the shape of the signal and background samples. Each source of systematic uncertainty is considered to be uncorrelated with other sources. They are listed below.

[7] The p_{T} requirement is applied to muons while the E_{T} requirement is applied to electrons.

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Luminosity and pile-up: the uncertainty in the integrated luminosity is 3.2%, affecting the overall normalisation of all processes estimated from the simulation. It is derived, following a methodology similar to that detailed in ref. [110], from a calibration of the luminosity scale using x−y beam-separation scans performed in August 2015 and May 2016. The uncertainty associated with the modelling of pile-up arises mainly from differences between the expected and observed fraction of the visible pp cross-section.

Lepton-related uncertainties: uncertainties associated with leptons arise from the reconstruction and identification efficiencies [70, 71], as well as lepton momentum scales and resolutions [71, 108]. The efficiencies are measured using tag-and-probe techniques on $Z \to \ell^+\ell^-$, $J/\psi \to \ell^+\ell^-$ and $\Upsilon \to \mu^+\mu^-$ data and simulated events. The small differences found are corrected for in the simulation. The combined effect of all these uncertainties results in an overall normalisation uncertainty in the signal and background ranging up to 10%. The dominant uncertainties arise in the reconstruction and identification of leptons.

MC background modelling: uncertainties in the factorisation and renormalisation scales, the parton shower, the choice of PDF, and the hadronisation and underlying-event model affect those backgrounds normalised with their theory cross-sections. Uncertainties in the modelling of $H \to ZZ^* \to 4\ell$ are found to be between 3% and 9% depending on the Higgs boson production mode, while for Standard Model $q\bar{q}/gg \to ZZ^*$ processes uncertainties from these sources add in quadrature to 5%.

Signal modelling: several sources of systematic uncertainty affect the theoretical modelling of the signal acceptance. Uncertainties originating from the choice of PDFs, the factorisation and renormalisation scales, and the modelling of parton shower, hadronisation, and underlying-event account for a total effect of 9% [92, 93].

Data-driven estimation of the background: uncertainties coming from the data-driven estimation of the background are also considered. They depend on the channel and affect the normalisation of the reducible background [79].

5.5 Results

The distribution of the invariant mass of the subleading dilepton pair m_{34} in the selected events in all four final states is shown in figure 2. The numbers of events observed in each channel after the event selection, as well as the expected background, are presented in table 2. A total of 102 events are observed for an expected background of 86.8 ± 7.5.

6 $H \to XX \to 4\ell$ ($15\,\text{GeV} < m_X < 60\,\text{GeV}$) analysis

6.1 Monte Carlo simulation

The signal process $H \to Z_dZ_d \to 4\ell$ was generated using the same model and event generator as in the $H \to ZZ_d \to 4\ell$ analysis. The model parameters ϵ and κ were adjusted so that only $H \to Z_dZ_d \to 4\ell$ decays were generated ($\kappa \gg \epsilon$). Contributions from final states with τ leptons are not considered. The mass of the Z_d boson was varied for different

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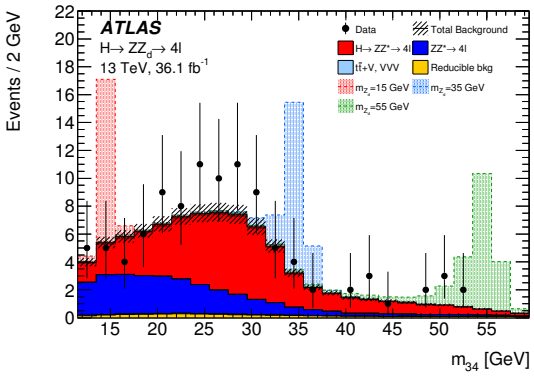

Figure 2. Distribution of m_{34} for data and background events in the mass range $m_{4\ell} \in [115, 130]$ GeV after the $H \to ZX \to 4\ell$ selection. Three signal points for the $H \to ZZ_d \to 4\ell$ model are shown. The signal strength corresponds to a branching ratio $\mathcal{B}(H \to ZZ_d \to 4\ell) = \frac{1}{3}\mathcal{B}(H \to ZZ^* \to 4\ell)$ (with $\mathcal{B}(H \to ZZ^* \to 4\ell)$ corresponding to the SM prediction [93]). The uncertainties include statistical and systematic contributions.

Process	$2\ell 2\mu$	$2\ell 2e$	Total
$H \to ZZ^* \to 4\ell$	34.3 ± 3.6	21.4 ± 3.0	55.7 ± 6.3
$ZZ^* \to 4\ell$	16.9 ± 1.2	9.0 ± 1.1	25.9 ± 2.0
Reducible background	2.1 ± 0.6	2.7 ± 0.7	4.8 ± 1.1
VVV, $t\bar{t} + V$	0.20 ± 0.05	0.20 ± 0.04	0.40 ± 0.06
Total expected	53.5 ± 4.3	33.3 ± 3.4	86.8 ± 7.5
Observed	65	37	102

Table 2. Expected and observed numbers of events in each channel after the $H \to ZX \to 4\ell$ event selection defined by the mass range $m_{4\ell} \in [115, 130]$ GeV. The uncertainties include MC-statistical and systematic components.

signal hypotheses in the range $15\,\text{GeV} < m_{Z_d} < 60\,\text{GeV}$ for $H \to Z_d Z_d \to 4\ell$, in steps of 5 GeV. The same signal normalisation was also applied (normalising to the SM Higgs boson production cross-section and $\mathcal{B}(H \to ZZ^* \to 4\ell)$).

For the signal process $H \to aa \to 4\mu$, the Higgs boson production was generated with the Powheg-Box v2 event generator [83–85] using the CT10 NLO PDFs [87]. Then this SM Higgs boson is replaced by a neutral scalar Higgs boson from the 2HDM+S [111] model. Pythia8 was used for the showering, hadronisation and underlying-event simulation in events generated where the Higgs boson decays to two pseudoscalar bosons that subsequently decay to pairs of muons, $H \to aa \to 4\mu$. The a-boson decay was done in the narrow-width approximation and the coupling to the muons is made to be that of a pseudoscalar. The mass of the a-boson was varied for five different signal hypotheses in the range $15\,\text{GeV} < m_a < 60\,\text{GeV}$.

The background processes considered in this analysis are similar to those featured in the $H \to ZZ_d \to 4\ell$ analysis described in section 5, however all the background processes

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are now reducible by vetoing on lepton pairs consistent with a Z boson (see section 6.2 for more details). The background processes, in order of decreasing importance, are as follows:

$H \to ZZ^* \to 4\ell$: the modelling of this process is the same as for the $H \to ZZ_d \to 4\ell$ analysis, as described in section 5.3. This background is approximately 63% of the total background prediction for this analysis.

$ZZ^* \to 4\ell$: the dominant $q\bar{q}$ production mechanism was modelled by Powheg-Box interfaced to Pythia8. The gg-initiated production mechanism was modelled in the same way as described for the $H \to ZZ_d \to 4\ell$ analysis. Both production mechanisms use the CT10 PDFs. This background is approximately 19% of the total background prediction.

VVV/VBS: higher-order electroweak processes (with cross-sections proportional to α^6 at leading order) include triboson production and vector-boson scattering, which lead to four leptons in the final state, with two additional particles (quarks, neutrinos, or electrons and muons). These processes were modelled by Sherpa 2.1.1 with the CT10 PDFs. Higgs boson production through VBF is subtracted from the estimates obtained with this event generator, in order to avoid double-counting this process in final background estimates. This background is approximately 17% of the total background prediction.

$Z + (t\bar{t}/J/\psi/\Upsilon) \to 4\ell$: this background process corresponds to the production of a Z boson, in association with either a quarkonium state ($b\bar{b}$ or $c\bar{c}$) that decays to leptons, or $t\bar{t}$ production with leptonic decays of the prompt W bosons. The processes involving quarkonia were modelled using Pythia8 with the NNPDF 2.3 PDFs [75]. The $t\bar{t}Z$ process was modelled at leading order with MadGraph5 [112] interfaced to Pythia8, using the NNPDF 2.3 PDFs [75] and the A14 tune [77]. These backgrounds are approximately 1% of the total background prediction.

Other reducible backgrounds: the same three SM processes of diboson WZ production, production of $t\bar{t}$ which decay semileptonically or fully leptonically and single Z production with associated jets are considered as in the $H \to ZZ_d \to 4\ell$ analysis, with the same modelling for the first two. The last one however was modelled by Powheg-Box interfaced to Pythia8 and the CTEQ6L1 PDFs [113]. The contribution from these processes is estimated to be negligible.

6.2 Event selection

After forming the possible SFOS quadruplets in each event (as described in section 5.2), the following selections are applied to the quadruplets: each quadruplet must not include more than one stand-alone or calorimeter-tagged muon, and the three leading leptons in the quadruplet must have $p_{\mathrm{T}} > 20$, 15, 10 GeV. Additionally, the leptons in the quadruplet must be matched to at least one of the triggers used to select the event at trigger-level, and a separation of $\Delta R > 0.1(0.2)$ is required for all same-flavour (different-flavour) leptons in the

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quadruplet. The event is discarded if no quadruplets remain. From any quadruplets remaining, a single quadruplet is selected as the one with the smallest dilepton invariant mass difference $\delta m = |m_{12} - m_{34}|$. This procedure for selecting a single quadruplet can result in the incorrectly paired quadruplet being selected in $4e$ or 4μ signal events. The fraction of signal events where this occurs was estimated using the $Z_d Z_d$ MC samples to be approximately 2% (1%) in the $4e$ (4μ) channel for $m_X = 15\,\text{GeV}$, rising to 8% (5%) at $m_X = 60\,\text{GeV}$. Events are classified into three channels according to the flavours of the leptons in the selected quadruplet: $4e$, $2e2\mu$, and 4μ (no distinction is made between $2e2\mu$ and $2\mu2e$ permutations).

The remaining selections are applied to the selected quadruplet of the event, with the event discarded if any selection fails: the four-lepton invariant mass must be in the range $115 < m_{4\ell} < 130\,\text{GeV}$, to select events consistent with a 125 GeV Higgs boson. The ratio of the secondary dilepton's mass to the primary dilepton's mass (m_{34}/m_{12}) must be greater than 0.85, which selects events where the dilepton masses are similar. Neither of the dilepton invariant masses is allowed to be in a mass range around the J/Ψ or Υ resonance masses (see table 1), with this requirement also applied to the alternative-pairing dilepton invariant masses (m_{14} and m_{32}) for events with a $4e$ or 4μ selected quadruplet. Finally, the dilepton invariant masses are required to be in the range $10 < m_{12,34} < 64\,\text{GeV}$ and in the case of $4e$ and 4μ quadruplets the alternative-pairing dilepton masses must be in the range $5 < m_{14,32} < 75\,\text{GeV}$. These last two selections suppress backgrounds that contain a Z boson, and are referred to as the *Z Veto* in the following.

6.3 Background estimation

All background estimates for this analysis rely on using MC simulations, and are validated in regions that are orthogonal to the signal event selection described in the previous section.

The two main background processes ($H \to ZZ^* \to 4\ell$ and $ZZ^* \to 4\ell$) are validated by comparison of the background prediction to data in three validation regions that are orthogonal to the signal region. The first validation region (VR1) is defined by reversing part of the *Z Veto* requirement: VR1 requires m_{14} or m_{32} to be greater than 75 GeV. The second validation region (VR2) instead requires that m_{12} is greater than 64 GeV. These two regions primarily validate the $H \to ZZ^* \to 4\ell$ prediction. The third validation region (VR3) reverses the requirement on the four-lepton invariant mass window, i.e. requires $m_{4\ell} < 115\,\text{GeV}$ or $m_{4\ell} > 130\,\text{GeV}$. In all three validation regions the $m_{34}/m_{12} > 0.85$ requirement is removed in order to increase the number of data events. Distributions of the average dilepton mass are shown for the three validation regions in figure 3.

The background estimates for the signal region are given in table 3, and include all systematic uncertainties described in section 6.4.

6.4 Systematic uncertainties

The systematic uncertainties in the signal and background modelling are the same as those described in section 5.4 (excluding the data-driven background uncertainties, which are not applicable to this search). It should be noted that fewer than four background events are predicted in the signal region for the $H \to XX \to 4\ell$ analysis, and therefore the dominant uncertainty in the background prediction is the statistical uncertainty.

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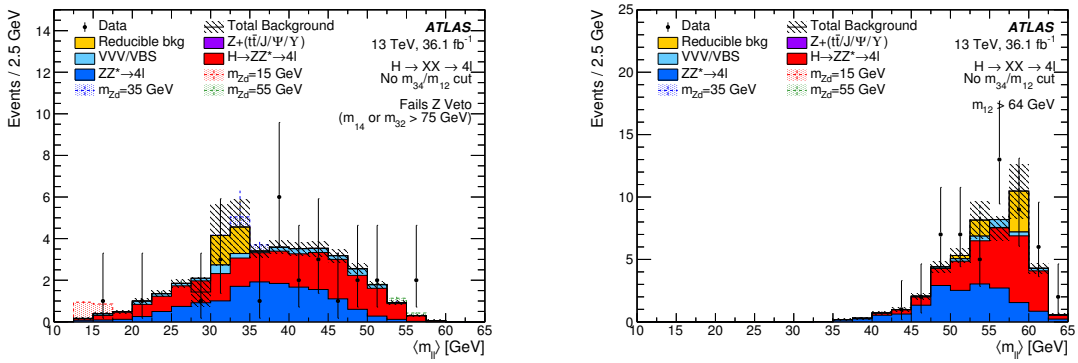
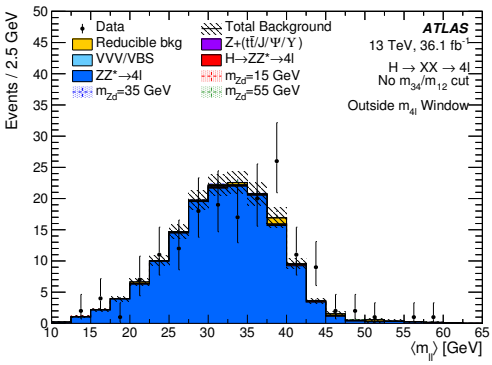


(a) VR1. **(b)** VR2.



(c) VR3.

Figure 3. Distributions of $\langle m_{\ell\ell}\rangle = \frac{1}{2}(m_{12} + m_{34})$ in three background validation regions of the $H \to XX \to 4\ell(15 < m_X < 60\,\text{GeV})$ analysis: (a) events failing the *Z Veto* ($4e$ or 4μ events where m_{14} or $m_{32} > 75\,\text{GeV}$), (b) events where $m_{12} > 64\,\text{GeV}$, (c) events outside of the $115 < m_{4\ell} < 130\,\text{GeV}$ window. In all cases the m_{34}/m_{12} requirement is removed to increase the number of events. The (negligible) contamination by the signal in these validation regions is shown for three mass hypotheses of the vector-boson benchmark model: the signal strength corresponds to a branching ratio $\mathcal{B}(H \to Z_d Z_d \to 4\ell) = \frac{1}{10}\mathcal{B}(H \to ZZ^* \to 4\ell)$ (with $\mathcal{B}(H \to ZZ^* \to 4\ell)$ corresponding to the SM prediction [93]).

6.5 Results

The distributions of $\langle m_{\ell\ell}\rangle = \frac{1}{2}(m_{12}+m_{34})$ for the events selected in this analysis are shown in figure 4, and the total yields presented in table 3: six events are observed for a prediction of 3.9 ± 0.3 events in the high-mass selection.

The biggest deviation from the Standard Model expectation is from a single event at $\langle m_{\ell\ell}\rangle \approx 20\,\text{GeV}$, with a local significance of $3.2\,\sigma$. The corresponding global significance is approximately $1.9\,\sigma$, estimated using an approximation [114] for the tail probability of the profile-likelihood-ratio test statistic. The significances are calculated using a Gaussian signal model with normalisation, yield, and standard deviation determined by interpolation between the corresponding fits to simulated signal samples (5 GeV intervals in Z_d mass). This statistical model, where the signal spans several bins of the $\langle m_{\ell\ell}\rangle$ distribution, means

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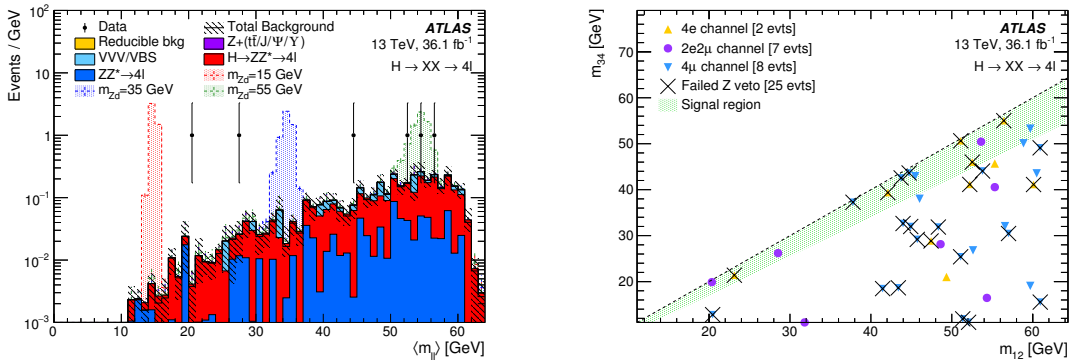
Process	Yield
$ZZ^* \to 4\ell$	0.8 ± 0.1
$H \to ZZ^* \to 4\ell$	2.6 ± 0.3
VVV/VBS	0.51 ± 0.18
$Z + (t\bar{t}/J/\Psi) \to 4\ell$	0.004 ± 0.004
Other Reducible Background	Negligible
Total	3.9 ± 0.3
Data	6

Table 3. Expected event yields of the SM background processes and observed data in the $H \to XX \to 4\ell$ ($15\,\text{GeV} < m_X < 60\,\text{GeV}$) selection. The uncertainties include MC-statistical and systematic components.



(a) Signal region $\langle m_{\ell\ell} \rangle$ distribution.

(b) m_{34} vs m_{12} distribution.

Figure 4. Distribution of (a) $\langle m_{\ell\ell} \rangle = \frac{1}{2}(m_{12} + m_{34})$ and (b) m_{34} vs m_{12}, for events selected in the $H \to XX \to 4\ell$ ($15 < m_X < 60\,\text{GeV}$) analysis. The example signal distributions in (a) correspond to the expected yield normalized with $\sigma(pp \to H \to Z_d Z_d \to 4\ell) = \frac{1}{10}\sigma_{\text{SM}}(pp \to H \to ZZ^* \to 4\ell)$. The crossed-through points in (b) fail the *Z Veto*. The events outside the (shaded green) signal region in figure (b) are events that fail the $m_{34}/m_{12} > 0.85$ requirement. The diagonal dashed line marks where $m_{12} = m_{34}$, and in this range of dilepton masses all events will have $m_{34} < m_{12}$.

that statistical fluctuations in the background estimate do not significantly impact the calculation of significance.

The m_{34} versus m_{12} distribution of the selected events is shown in figure 4b. In this figure, the crossed-through markers correspond to the events that fail the *Z Veto*, which required the alternative-pairing masses m_{32} and m_{14} (relevant only to the $4e$ and 4μ channels) to be less than 75 GeV. This requirement has a significant impact on the signal efficiency (up to $\approx 40\%$ loss) for m_X just above 15 GeV, but is applied in this analysis to mitigate any small contributions from SM processes involving Z boson production with large cross-sections. The 25 events that fail this veto are shown in validation region VR1 in figure 3, where there is a total background prediction of 38 ± 3 events.

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7 $H \to XX \to 4\mu$ ($1\,\text{GeV} < m_X < 15\,\text{GeV}$) analysis

7.1 Monte Carlo simulation

The generation of the signal processes $H \to Z_d Z_d \to 4\ell$ and $H \to aa \to 4\mu$ follows the prescription described in section 6.1. Four samples were generated with Z_d masses of 1 GeV, 2 GeV, 5 GeV and 10 GeV, while the mass of the a-boson was varied for 10 different signal hypotheses in the range $0.5\,\text{GeV} \leq m_a \leq 15\,\text{GeV}$.

The background processes considered in this analysis are described in the following:

$H \to ZZ^* \to 4\ell$: the modelling of this process is the same as for the $H \to ZZ_d \to 4\ell$ analysis, described in section 5.1.

$ZZ^* \to 4\ell$: this process was simulated with Sherpa 2.1.1 due to an implicit particle-level requirement on the mass of the Z^* in the Powheg-Box MC sample used for the high-mass selection described in section 6.1. The gg-initiated production mechanism was modelled in the same way as for the $H \to ZZ_d \to 4\ell$ analysis, see section 5.1. Both production mechanisms are estimated using the CT10 PDFs.

VVV/VBS: the modelling of this process is described in section 6.1.

7.2 Event selection

In this search, only events with at least four muons are considered. Similarly to the searches described above, the selected muons are combined into 4μ quadruplets in all possible permutations of pairs of opposite-sign dimuons. In the case of having more than four muons, the different quadruplets that can be formed are all considered. Of the muons in each quadruplet, at least three must have $p_\text{T} > 10\,\text{GeV}$, at least two must have $p_\text{T} > 15\,\text{GeV}$, and at least one must have $p_\text{T} > 20\,\text{GeV}$, and there cannot be more than one stand-alone or calorimeter-tagged muon.

The quadruplet selection closely follows the selection described in section 6.2. Nonetheless, low-mass bosons are more boosted and muons less separated. For this reason, to keep signal efficiencies high, no ΔR requirement is applied to the muons of the quadruplets. If more than one quadruplet survives this selection, the one with the smallest $\Delta m_{\ell\ell}$ is selected.

Similarly to the $H \to XX \to 4\ell$ ($15 < m_X < 60\,\text{GeV}$) analysis, a set of requirements are applied to the quadruplet invariant masses as well as to the masses of the different muon pairings in the quadruplet. The quadruplet invariant mass must satisfy $120\,\text{GeV} < m_{4\ell} < 130\,\text{GeV}$. This window is tighter than the selections described in sections 5.2 and 6.2 because muons have smaller radiative losses than electrons. The dilepton masses must be in the range $0.88\,\text{GeV} < m_{12,34} < 20\,\text{GeV}$. No restriction is applied to the alternative-pairing dilepton masses because more than one third of signal events in this corner of the phase space contains an alternative-pairing dilepton mass that satisfies $75\,\text{GeV} < m_{14,32} < 125\,\text{GeV}$, and would therefore be lost if this selection was applied.

7.3 Background estimation

The main background contributions for this search come from the $ZZ^* \to 4\ell$ and $H \to ZZ^* \to 4\ell$ processes, as for the $H \to XX \to 4\ell$ ($15 < m_X < 60\,\text{GeV}$) case described in

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section 6.3. These backgrounds, suppressed by the requirements on the lepton invariant mass, account for 30% each of the total background. Smaller background contributions come from higher-order electroweak processes (with cross-sections proportional to α^6 at leading order) and account for approximately 19% or the total background. Finally, events with multiple heavy flavour (bottom or charm) quark decays can also contribute to the total background yield. A leading part of this contribution comes from double semileptonic decays, where the b-quark decays to a muon and a c-quark which further decays into another muon and light hadrons. Resonances produced in the heavy flavour quark decay chain (i.e. ω, ρ, ϕ, J/ψ) that result in pairs of muons also become an important contribution of this background. Events with four heavy flavour quarks may pass the signal region requirements if each bottom or charm quark decays semileptonically.

The estimation method for the heavy flavour background was developed using fully data-driven inputs and inspired by a previous analysis from CMS [115]. Using data control samples, the background is modelled as a two-dimensional template in the plane of the invariant masses of the two dimuons. This template is constructed from the Cartesian product of two one-dimensional dimuon invariant mass spectra assuming that each muon pair is independent of the other. The one-dimensional templates are derived in control regions with three muons passing the same quality and isolation requirements used elsewhere in the analysis. The high-p_{T} selection requires three muons, with a muon pair with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ matched to the dimuon trigger, and an additional muon with $p_{\mathrm{T}} > 5\,\mathrm{GeV}$. The low-$p_{\mathrm{T}}$ selection also requires three muons, with a pair of muons, each with $p_{\mathrm{T}} > 5\,\mathrm{GeV}$, and an additional muon with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ matched to the single-muon trigger. The choice of p_{T} thresholds for the templates was carefully studied and it is required that the first (second) dimuon pair always passes the high-p_{T} (low-p_{T}) selection. Estimations with alternative p_{T} threshold selections were found to be compatible with the current prescription. The Higgs boson mass requirement described in section 4 introduces a correlation between the dimuon pairs and therefore a correction to the two-dimensional template is necessary. This correction is extracted from data using a sample enriched in events with heavy flavour quarks, with inverted isolation and vertex requirements. The final template covers the full m_{34} vs m_{12} plane, including the signal region (defined by the condition $m_{34}/m_{12} > 0.85$). The normalisation of the template is computed in the region with $m_{34}/m_{12} < 0.85$, and its effect propagated to the signal region. The heavy flavour processes are negligible in the high-mass region, while they account for 22% of the total prediction in the low-mass region.

The modelling of the most important background processes ($ZZ^* \to 4\ell$ and $H \to ZZ^* \to 4\ell$) was validated in VR1, VR2 and VR3, defined in section 6.3 for the $H \to XX \to 4\ell$ ($15 < m_X < 60\,\mathrm{GeV}$) selection. The $ZZ^* \to 4\ell$ process can also be validated by comparing the background prediction to the data in a validation region (VR4) that is orthogonal to this signal region. This validation region is defined by reversing the four-lepton invariant mass window requirement, i.e. $m_{4\ell} < 120\,\mathrm{GeV}$ or $m_{4\ell} > 130\,\mathrm{GeV}$. The average dilepton mass distribution for this region is shown in figure 5.

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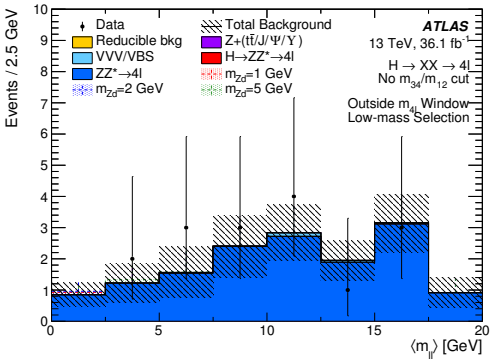

Figure 5. Distribution of $\langle m_{\ell\ell}\rangle = \frac{1}{2}(m_{12} + m_{34})$ in the validation region. The (negligible) contamination by the signal in these validation regions is shown for three mass hypotheses of the vector-boson benchmark model: the signal strength corresponds to a branching ratio $\mathcal{B}(H \to Z_d Z_d \to 4\ell) = \frac{1}{10}\mathcal{B}(H \to ZZ^* \to 4\ell)$ (with $\mathcal{B}(H \to ZZ^* \to 4\ell)$ corresponding to the SM prediction [93]).

7.4 Systematic uncertainties

In addition to the systematic uncertainties described in section 6.4, this analysis includes additional uncertainties for its data-driven background estimate.

Several sources of uncertainty are considered for the heavy flavour background data-driven estimation. Uncertainties in the shape of the one-dimensional templates are propagated to the two-dimensional template to account for shape variations in the dimuon invariant mass spectra. Different parameterisations of the Higgs boson mass requirement are also considered for modelling the effect of this condition on the shape of the distribution in the (m_{12}, m_{34}) plane. The previous two systematic uncertainties affect the shape of the two-dimensional plane, which propagates to a 63% effect on the yield of the heavy flavour background in the low-mass search signal region. Finally, the statistical uncertainty in the normalisation of the template in the signal region ($m_{34}/m_{12} < 0.85$ region of the two-dimensional plane) is also propagated to the signal region to account for fluctuations in the final heavy flavour background yields and has an effect of 13%. Uncertainties from the different sources are added in quadrature, and the total amounts to 65% for this background source.

7.5 Results

The $\langle m_{\ell\ell}\rangle$ distribution for the selected events is shown in figure 6a. Table 4 shows the resulting yields and uncertainties for this analysis: no events are observed to pass the selection, for a total background prediction of 0.4 ± 0.1.

The m_{34} versus m_{12} distribution in figure 6b shows that there is no evidence of a signal-like resonance even outside of the $120\,\text{GeV} < m_{4\ell} < 130\,\text{GeV}$ window applied in this selection: 16 events are observed outside of this mass window, compared to a MC-based prediction of 15 ± 2 events from non-resonant SM ZZ processes. These 16 events are shown in the validation region in figure 5.

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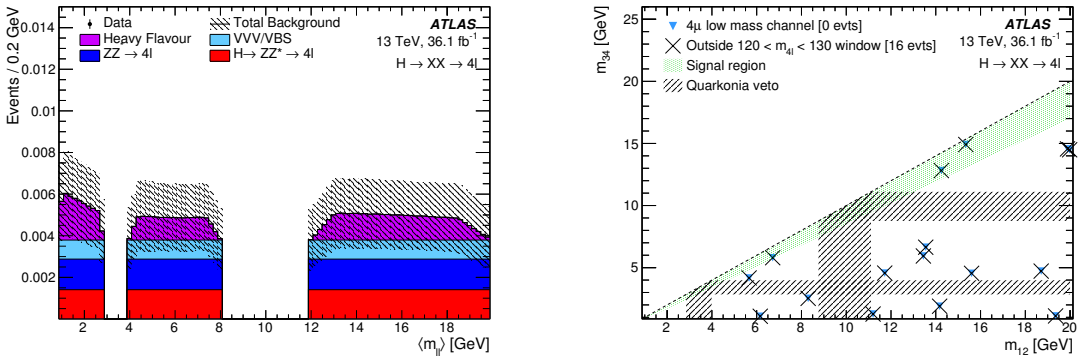

(a) Signal region $\langle m_{\ell\ell}\rangle$ distribution.

(b) m_{34} vs m_{12} distribution.

Figure 6. Distribution of (a) $\langle m_{\ell\ell}\rangle = \frac{1}{2}(m_{12}+m_{34})$ and (b) m_{34} vs m_{12}, for events selected in the $H \to XX \to 4\mu(1 < m_X < 15\,\text{GeV})$ analysis. The crossed-through points in figure (b) correspond to events that are outside the $m_{4\ell}$ mass window of $120\,\text{GeV} < m_{4\ell} < 130\,\text{GeV}$. The events outside the (shaded green) signal region are events that fail the $m_{34}/m_{12} > 0.85$ requirement.

Process	Yield
$ZZ^* \to 4\ell$	0.10 ± 0.01
$H \to ZZ^* \to 4\ell$	0.1 ± 0.1
VVV/VBS	0.06 ± 0.03
Heavy flavour	0.07 ± 0.04
Total	0.4 ± 0.1
Data	0

Table 4. Expected event yields of the SM background processes and observed data in the $H \to XX \to 4\mu$ ($1\,\text{GeV} < m_X < 15\,\text{GeV}$) selection. The uncertainties include MC-statistical and systematic components (systematic uncertainties are discussed in section 7.5).

8 Interpretation and discussion

The results do not show evidence for the signal processes of $H \to ZX \to 4\ell$ or $H \to XX \to 4\ell$. The results are therefore interpreted in terms of limits on the benchmark models presented in section 2.

For the $H \to ZX \to 4\ell$ analysis, the signal shape is obtained directly from simulation using the $Z_{(d)}Z_d$ benchmark model [14, 15]. For the $H \to XX \to 4\ell$ analysis, a simple Gaussian model is used for a generic signal in the $\langle m_{\ell\ell}\rangle$ observable, with the mean and standard deviation depending on the mass scale and resolution, respectively, in each decay channel. These scales and resolutions are estimated directly from simulation. The mass scale is found to have a -2% bias in $X \to ee$ decays, and -0.5% bias in $X \to \mu\mu$ decays (i.e. a -1% bias is used in the $ee\mu\mu$ channel). The mass resolutions are estimated to be 3.5% in $X \to ee$ decays and 1.9% in $X \to \mu\mu$ decays (meaning, for example, that the standard deviation in the 4μ channel is about $1/\sqrt{2} \times 1.9\% \approx 1.34\%$ of m_X). These scales and resolutions are valid across the full mass range considered (1–60 GeV).

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8.1 Limits on fiducial cross-sections

The results were interpreted as limits on fiducial cross-sections by estimating the reconstruction efficiencies of each channel ϵ_c in the fiducial phase spaces defined in table 5. The fiducial selections were chosen to mimic the analysis selections described in sections 5.2 and 6.2. The leptons are "dressed", i.e. in order to emulate the effects of quasi-collinear electromagnetic radiation from the charged leptons on their experimental reconstruction in the detector [116], the four-momenta of all prompt photons within $\Delta R = 0.1$ of a lepton are added to the four-momentum of the closest lepton. For the $H \to XX$ search the efficiencies (shown in figure 8a) are estimated with the Z_dZ_d benchmark model and were verified to be compatible with the aa benchmark model to within 3% across the whole mass range. For the ZX search the efficiencies (shown in figure 7a) are estimated with the ZZ_d benchmark model, but no verification was explicitly made to confirm if these efficiencies are valid for a Za process. Assuming that the verified compatibility between efficiencies of Z_dZ_d and aa processes applies equally to ZZ_d and Za processes, upper limits on the cross-sections corresponding to these fiducial phase spaces should be applicable to any models of 125 GeV Higgs boson decays to four leptons via one (with an associated Z boson) or two intermediate, on-shell, narrow, promptly decaying bosons. The fiducial requirements are applied to the four leptons in this decay. These efficiencies are used to compute 95% CL upper limits on the cross-sections in the fiducial phase spaces defined for the $H \to ZX \to 4\ell$ and $H \to XX \to 4\ell$ searches. These model-independent limits are computed using the $\mathrm{CL_s}$ frequentist formalism [117] with the profile-likelihood-ratio test statistic [118] (systematics are represented with nuisance parameters which are then profiled in the calculation of the test statistic). The results are shown in figures 7b and 8b, respectively. Impact of the systematic uncertainties on the limits is small.

For the $H \to ZX \to 4\ell$ search, a local excess of 3σ at $m_{Z_d} = 23\,\mathrm{GeV}$ is observed in the $2\ell 2e$ channel. However, the total observed and predicted event counts in this channel agree within 0.5σ. No local excess is observed in the $2\ell 2\mu$ channel.

The width of the 2σ expected limit bands of figure 8b increases towards large values of m_X because more events are expected from background-only processes at this end of the mass spectrum; the larger expected background leads to a greater spread in the limits obtained with pseudoexperiments generated with the background-only hypothesis.

8.2 Limits on branching ratios

Model-dependent acceptances for the fiducial phase spaces are computed per channel for the $H \to ZZ_d \to 4\ell$ and $H \to XX \to 4\ell$ searches. The acceptance for the benchmark vector-boson model is estimated for both searches, whereas the acceptance for the benchmark pseudoscalar-boson model (type-II 2HDM+S model with $\tan\beta = 5$) is estimated only for the $H \to XX \to 4\ell$ search. The acceptances are used in a combined statistical model to compute upper limits on $\sigma_H \times \mathcal{B}(H \to ZZ_d \to 4\ell)$ and $\sigma_H \times \mathcal{B}(H \to XX \to 4\ell)$ for each model. The Z_d model assumes partial fractions of 0.25:0.25:0.25:0.25 for the $4e$:$2e2\mu$:4μ:$2\mu 2e$ channels, whereas the a model assumes 100% decay to 4μ. These cross-section limits are converted into limits on the branching ratios of $H \to ZZ_d$, $H \to Z_dZ_d$

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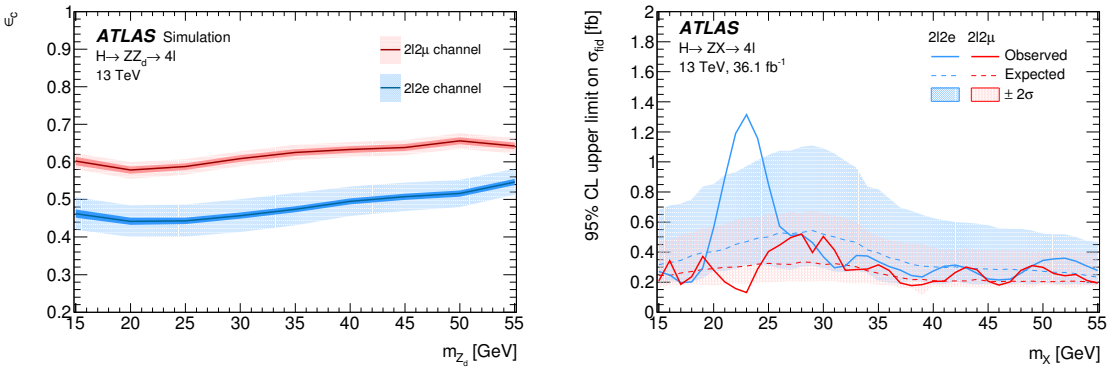
	$H \to ZX \to 4\ell$ ($15\,\text{GeV} < m_X < 55\,\text{GeV}$)	$H \to XX \to 4\ell$ ($15\,\text{GeV} < m_X < 60\,\text{GeV}$)	$H \to XX \to 4\mu$ ($1\,\text{GeV} < m_X < 15\,\text{GeV}$)
Electrons	Dressed with prompt photons within $\Delta R = 0.1$ $p_\text{T} > 7\,\text{GeV}$ $\lvert\eta\rvert < 2.5$		
Muons	Dressed with prompt photons within $\Delta R = 0.1$ $p_\text{T} > 5\,\text{GeV}$ $\lvert\eta\rvert < 2.7$		
Quadruplet	Three leading-p_T leptons satisfy $p_\text{T} > 20\,\text{GeV}, 15\,\text{GeV}, 10\,\text{GeV}$		
	$\Delta R > 0.1$ (0.2) between SF (OF) leptons		—
	$50\,\text{GeV} < m_{12} < 106\,\text{GeV}$ $12\,\text{GeV} < m_{34} < 115\,\text{GeV}$ $115\,\text{GeV} < m_{4\ell} < 130\,\text{GeV}$ $m_{12,34,14,32} > 5\,\text{GeV}$	$m_{34}/m_{12} > 0.85$	
		$10\,\text{GeV} < m_{12,34} < 64\,\text{GeV}$ $5\,\text{GeV} < m_{14,32} < 75\,\text{GeV}$ if $4e$ or 4μ	$0.88\,\text{GeV} < m_{12,34} < 20\,\text{GeV}$
		Reject event if either of: $(m_{J/\psi} - 0.25\,\text{GeV}) < m_{12,34,14,32} < (m_{\psi(2S)} + 0.30\,\text{GeV})$ $(m_{\Upsilon(1S)} - 0.70\,\text{GeV}) < m_{12,34,14,32} < (m_{\Upsilon(3S)} + 0.75\,\text{GeV})$	

Table 5. Summary of the fiducial phase-space definitions used in this analysis, appropriate for processes of the form $H \to ZZ_d \to 4\ell$ aand $H \to XX \to 4\ell$, where X is a promptly decaying, on-shell, narrow resonance.



(a) Efficiencies. **(b)** Fiducial cross-sections.

Figure 7. (a) Per-channel efficiencies ϵ_c calculated in the fiducial volume described in the $H \to ZX \to 4\ell$ column of table 5. The dark band is the statistical uncertainty and the lighter band is the systematic uncertainty. These efficiencies were computed using the $H \to ZZ_d \to 4\ell$ model. (b) Upper limits at the 95% CL on fiducial cross-sections for the $H \to ZX \to 4\ell$ process. The limits from the $H \to Za \to 4\ell$ search are valid only for the $2\ell 2\mu$ channel as the $H \to Za$ model assumes $\mathcal{B}(a \to \mu\mu) = 100\%$.

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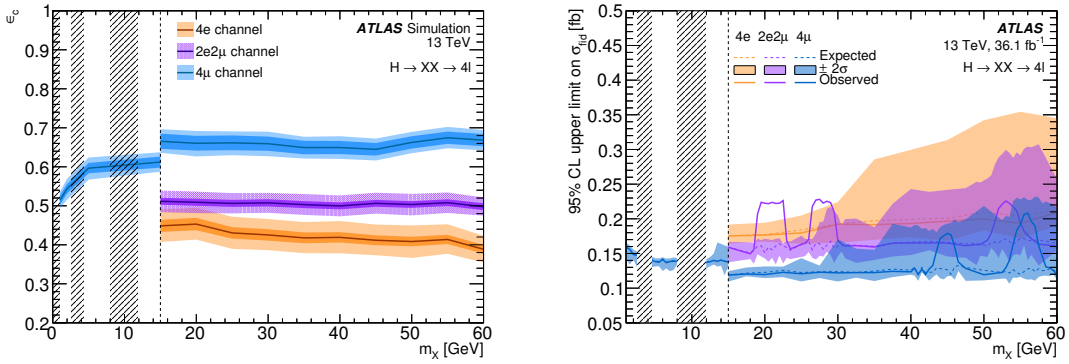

(a) Efficiencies. **(b)** Fiducial cross-sections.

Figure 8. (a) Model-independent per-channel efficiencies ϵ_c calculated in the fiducial volumes described in the 1 GeV $< m_X <$ 15 GeV and 15 GeV $< m_X <$ 60 GeV columns of table 5 (i.e. separate phase spaces are defined for m_X above and below 15 GeV). The dark band is the statistical uncertainty and the lighter band is the systematic uncertainty. (b) Upper limits at the 95% CL on fiducial cross-sections for the for the $H \to XX \to 4\ell$ process. The step change in the fiducial cross-section limit in the 4μ channel is due to the change in efficiency caused by the change in fiducial phase-space definition. The shaded areas are the quarkonia veto regions.

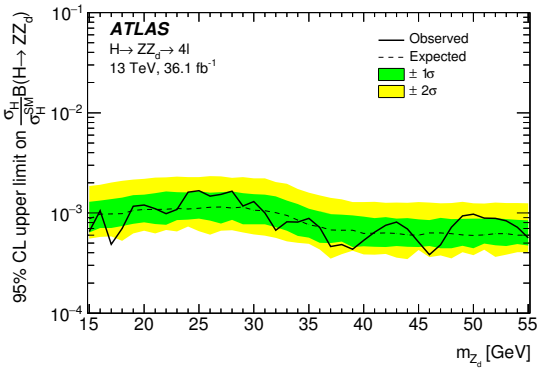

Figure 9. Upper limit at 95% CL on the branching ratio for the $H \to ZZ_d$ process.

and $H \to aa$ by using the theoretical branching ratios for $Z_d \to \ell\ell$ and $a \to \mu\mu$ from each benchmark model [14, 15], and assuming for σ_H the SM cross-section[8] for Higgs boson production at $\sqrt{s} = 13$ TeV [93]. The limits on these branching ratios are shown in figures 9 and 10 for the $H \to ZZ_d \to 4\ell$ and $H \to XX \to 4\ell$ searches, respectively. The observed limit for $\mathcal{B}(H \to aa)$ (figure 10b) for $m_a > 15$ GeV is greater than 1 (i.e. this search has no sensitivity to this model in that mass range). The limit on the branching ratio for $H \to Z_dZ_d \to 4\ell$ improves on the Run 1 result of ref. [39] by about a factor of four, which corresponds to the increase in both luminosity and Higgs boson production cross-section between Run 1 and Run 2.

[8]This assumes that the presence of BSM decays of the Higgs boson does not signicantly alter the Higgs boson production cross-section from the SM prediction.

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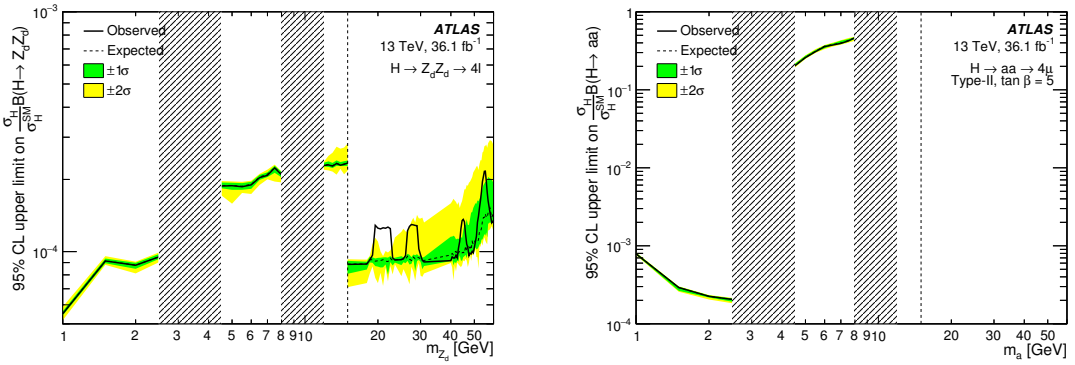

(a) $H \to Z_d Z_d$. **(b)** $H \to aa$.

Figure 10. Upper limit at 95% CL on the branching ratios for processes (a) $H \to Z_d Z_d$ and (b) $H \to aa$, for the two benchmark models studied in this paper. The limit on $H \to aa$ is greater than 1 for $m_a > 15\,\text{GeV}$. The step change in (a) at the $m_X = 15\,\text{GeV}$ boundary is due to the addition of sensitivity to 4e and $2e2\mu$ final states (lowering the limit). The shaded areas are the quarkonia veto regions.

9 Conclusion

Searches are performed for exotic decays of the Standard Model Higgs boson with a mass of 125 GeV to one or two new spin-1 particles, $H \to ZZ_d$ and $H \to Z_d Z_d$, or spin-0 particles, $H \to Za$ and $H \to aa$, using proton-proton collision data produced at $\sqrt{s} = 13\,\text{TeV}$ and recorded by the ATLAS detector at the LHC in 2015 and 2016. The data correspond to a combined integrated luminosity of 36.1 fb^{-1}. The searches explore the final state consisting of four leptons (electrons or muons) produced from the prompt decays of the intermediate boson states. The search targeting the ZX intermediate state is sensitive to Z_d masses between 15 and 55 GeV, and the search targeting the XX intermediate state is sensitive to Z_d masses between 15 and 60 GeV. Intermediate states of XX ($X = a$ or Z_d) where the boson mass m_X is between 1 and 15 GeV (excluding masses near known dilepton resonances from quarkonium states) are searched for in events with four muons.

The data are found to be globally consistent with SM background predictions. Upper limits (dependent on the mass of the intermediate exotic boson) are set on the branching ratio of Higgs boson to ZZ_d, $Z_d Z_d$, and aa, corresponding to $\mathcal{B}(H \to ZZ_d) \approx 0.1\%$, $\mathcal{B}(H \to Z_d Z_d) \approx 0.01\%$, and $\mathcal{B}(H \to aa) \approx 1\%$ respectively (depending on mass range). These limits are obtained under the assumption of a SM production cross-section for Higgs bosons, and assume prompt decay of the exotic bosons. Limits on fiducial cross-sections are also computed, which can be used for testing models different from the benchmark models used in this paper.

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